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Stress-corrosion cracking (SCC) is a cracking process caused by the conjoint action of stress and a corrodent. Traditionally, the stress that causes SCC has been regarded as a sustained tensile stress. When corrosion-assisted cracking is caused by cyclic stress, the problem is termed corrosion fatigue. Thus, test methods for SCC rely upon static (or quasi-static) tensile loading. However, in recent years researchers have developed new information showing that, at least in certain instances, small-amplitude cyclic loading superimposed on high tensile loads (ripple-loading) can have a significant influence on SCC behavior. The trend revealed is that ripple-loading reduces the apparent SCC stress or stress-intensity threshold and accelerates time-to-failure for stresses or stress-intensities above threshold levels. The implication of these findings is that traditional static tests for SCC may, in fact, be non-conservative. The mechanism of ripple-load cracking is thought to involve film rupture at active SCC sites. The recent literature on ripple-loading has been identified and reviewed. Several notable examples have been cited and discussed. Directions for further study are delineated.

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CONTENTS

A LITERATURE REVIEW ON THE INFLUENCE OF SMALL-AMPLITUDE CYCLIC LOADING ON STRESS-CORROSION CRACKING IN ALLOYS

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INTRODUCTION

Stress-corrosion cracking (SCC) is a cracking process caused by the conjoint action of stress and a corrodent [1]. Conceptually, SCC will occur if a sensitive material is exposed to a corrosive environment under sufficient stress for a sufficient length of time. The stress required is related to a threshold level above which SCC can occur. The time required is related to an incubation beyond which SCC can occur.

Traditionally, the stress that causes SCC has been regarded as a sustained tensile stress. Thus, SCC is often regarded as a "static" failure process. If corrosion-assisted cracking is caused by cyclic stress, then the problem is termed "corrosion fatigue" and it is often assigned to another category of phenomena.

Test methods for SCC have envolved around the use of static (or quasi-static) tensile loading [2]. Many of the most widely used test methods in SCC involve specimens which are stressed under constant displacement by being self-loaded or placed in simple bolt-loaded fixtures. However, in recent years very slow strain-rate effects have been shown to play an important role in SCC and newer test methods using constant-extension strain rate as an experimental variable have evolved [3]. Nevertheless, constant-load or constant-displacement test techniques still predominate in SCC testing.

In recent years, several investigators have shown that small-amplitude cyclic loading superimposed on a sustained tensile load (ripple-loading) can significantly affect SCC behavior [4-8]. The trend revealed is that ripple-loading reduces the time-to-failure for SCC test specimens and reduces the apparent stress or stress-intensity threshold below which SCC is not observed to occur. The implication of these findings is that traditional constant-load or constant-displacement SCC test methods may produce nonconservative results.

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RESULTS OF THE LITERATURE SURVEY

The first reference to a phenomenon akin to ripple-loading effects found by the authors were reported in 1970 by Endo and Komai in a somewhat anecdotal manner [9]. Endo and Komai studied the effect of a high-frequency small-amplitude cyclic stress superimposed on the hold period of a low-frequency large-amplitude trapezoidal waveform in corrosion fatigue. The material studied in their investigation was high-carbon (0.90 wt.-percent) quenched-and-tempered steel with a yield strength of 128 ksi (883 MPa). Endo and Komai referred to the steel as being insensitive to SCC. Unnotched cantilever specimens were tested in 1 percent NaCl aqueous solution at the freely corroding potential. Comparisons are based upon cycles-to-failure data, however, the crack propagation period was judged by Endo and Komai to be short because of the material's brittleness.

Endo and Komai compared the fatigue life of specimens cycled under a one-cycle-per-hour (1 cph) trapezoidal wave form (maximum stress unspecified) without superimposed small-amplitude secondary cyclic stresses and with secondary cyclic stresses equaling 5 percent and 10 percent (R = minimum stress/maximum stress = 0.95 and 0.90), respectively, of the maximum stress. The secondary stresses were applied at a frequency of 38 cycles per minute (cpm). Afer 336 large-amplitude cycles, no failures were observed in specimens tested without the secondary stresses. However, failures occurred after just 6 and 10 cycles, respectively, with the 10 percent secondary stresses (R = 0.90) and after 19 cycles with the 5 percent secondary stresses (R = 0.95).

Endo and Komai concluded that the small-amplitude secondary cyclic stresses demonstrated remarkably damaging effects on corrosion-fatigue life.

In a subsequent paper published in 1978, Endo and Komai devoted the entire paper to the influences of secondary stress fluctuations of small amplitude on low-cycle corrosion fatigue [10]. In this complex investigation, Endo and Komai studied two materials, an as-rolled C-Mn steel with a yield strength of 72 ksi (500 MPa) and a heat-treated Al-Zn-Mg alloy with a yield strength of 34 ksi (235 MPa). The steel is described as being insensitive to SCC and the aluminum alloy is described as being highly sensitive to SCC under freely corroding conditions in the 1 percent NaCl deionized water solution used as the environment in this study.

The study included numerous variables. Both materials were tested for cycles-to-failure corrosion-fatigue life and for crack growth rates. The primary variables were the amplitude and frequency of the sinusoidal secondary stress cycles superimposed on the low-frequency trapezoidal primary waveforms. The frequencies of the primary waveforms were either 1 or 2 cph. The frequencies of the secondary waveforms were either 3.9, 40 or 200 cpm. The amplitudes of the secondary waveforms varied from 5 to 75 percent of the primary waveform amplitudes (R = 0.95 to 0.25).

For the SCC-insensitive steel, Endo and Komai confirmed the findings of their previous study [9], i.e., small secondary stress fluctuations can greatly reduce corrosion-fatigue life. However, the effects of secondary stress fluctuations on corrosion-fatigue life were found to be highly complex, owing to competing failure mechanisms involving corrosive surface attack and fatigue crack initiation. It was found that, under certain specific conditions of corrosive attack and secondary loading amplitude, an equilibrium could be reached where each factor negated the other and no effect on fatigue occurred. However, both below and above this equilibrium level of secondary cyclic loading amplitude, corrosion-fatigue life was significantly reduced by secondary loading.

For the SCC-sensitive aluminum alloy, a different but similarly complex picture emerged from the studies of Endo and Komai. Here, the primary effects of secondary loading were apparent in the crack growth rate data. Surprisingly, the small-amplitude secondary loading significantly reduced the crack growth rates for maximum stress-intensity (K_{max}) levels above the static SSC threshold (K_{Iscc}) [11]. It was hypothesized by Endo and Komai that this phenomenon was caused by the secondary cyclic loading acting to promote corrosive dissolution at SCC crack tips, which blunted the crack tips and lowered the effective stress-intensity.

In roughly the same time period, Dawson and Pelloux studied the onset of SCC in alpha + beta titanium alloys under cyclic loading [12]. Although their paper does not deal specifically with small-amplitude loading and high R-values, it does contain some interesting observations on the relationship between corrosion-fatigue crack growth and SCC in high-strength titanium alloys.

Dawson and Pellox studied two alloys, Ti-6Al-4V and Ti-6Al-6V-2Sn, in 0.6M NaCl aqueous solution at room temperature using a haversine waveform and R = 0.1. In accordance with other investigators studying similar titanium alloys, Dawson and Pelloux found a pronounced increase in crack growth rate (da/dN) associated with the onset of SCC superimposed on the cyclic corrosion-fatigue crack growth rate. The stress-intensity range (ΔK) level associated with the sudden acceleration in da/dN under cyclic loading was termed ΔK_{scc} by Dawson and Pelloux. This term is derived from the static SCC threshold parameter, K_{Iscc}, proposed by Brown [11].

The ΔK_{scc} threshold was observed to be a function of cyclic frequency. ΔK_{scc} levels were found to vary inversely with cyclic frequency and ΔK_{scc} levels tended to fall below static K_{Iscc} values, except at low cyclic frequencies on the order of 0.1 Hz where the two merged. In effect, the static K_{Iscc} was shown to be a nonconservative upper bound value for the onset of SCC under cyclic loading.

This environmentally-assisted cracking behavior was explained by Dawson and Pelloux in terms of passivation. The ΔK_{scc} transition was taken to represent the point at which transgranular cleavage fracture of alpha grains can no longer be suppressed by repassivation of the freshly-exposed surfaces at the tip of the growing crack. Based upon this passivation concept, ΔK_{scc} levels vary inversely with cyclic frequency because at higher frequencies the opportunity for repassivation under cyclic loading diminishes. Thus, higher frequency cyclic loading promotes the onset of SCC. This work by Dawson and Pelloux was among the first to introduce the concept of crack-tip film formation and rupture in affecting SCC under cyclic loading. Dawson later conducted a subsequent study which provided further evidence to support the concept of crack-tip passivation behavior controlling environmental cracking behavior under cyclic loading in titanium alloys [13].

In a 1977 paper, Parkins and Greenwell [4] set about to examine the validity of the linear superposition model for combining static and cyclic crack growth rates in corrosion fatigue [14-16]. Parkins and Greenwell studied a mild steel in a carbonate-bicarbonate solution at -650 mV (SCE) and 75 deg. C. The static K_{Iscc} for intergranular SCC was found to be 19 ksi$\sqrt{in.}$ (21 MPa$\sqrt{m}$) using constant deflection tests. However, under cyclic loading at 0.19 Hz with $K_{max} \leq K_{Iscc}$, intergranular cracking was observed at K_{max} values as low as 9 ksi$\sqrt{in.}$ (10 MPa$\sqrt{m}$). Transgranular cracking was observed under other conditions, viz, higher ΔK and cyclic frequency, but intergranular cracking was associated with SCC in this material and transgranular cracking was associated with corrosion-assisted fatigue.

Based upon the experimental results reported in this paper, Parkins and Greenwell concluded that the interface between SCC and corrosion fatigue may involve synergistic effects that fall outside the boundry conditions for simple superposition models. They also concluded that, for the material/environment/potential conditions of their experiments, K_{Iscc} can be lowered by a least 60 percent due to cyclic loading as compared to the value obtained under static conditions. This paper casts further doubt on the inherent conservatism of applying conventional K_{Iscc} data to situations involving cyclic loading.

In a 1979 report [17], Ford discusses the design significance of the K_{Iscc} threshold parameter in terms of basic environmental cracking mechanisms. He points out that it is the oxide-rupture rate at the crack tip which is of fundamental importance to environmental cracking behavior, not stress-intensity per se. He proceeds to develop a theoretical prediction of K_{Iscc} and calculates a theoretical value for aluminum alloys.

This value turns out to be at least an order of magnitude lower than experimentally observed values. Several reason are cited to account for this large discrepancy. The reason described by Ford as most likely is the fact that the theoretical calculation assumes a bare metal surface at the crack tip when, in fact, the crack tip is predominately oxide-covered thereby increasing the actual measured value of K_{Iscc}.

Thus, Ford asserts that cyclic loading, which disrupts oxide film formation, will act to lower the apparent K_{Iscc} threshold. He cites a number of experimental studies which support his hypothesis [18-20]. However, in no case has an experimentally observed value of K_{Iscc} been found which approaches his theoretically derived minimum value. Ford attributes this discrepancy to some unknown mechanical factor.

In 1980 paper [5], Ford and Silverman described an experimental investigation of environmental cracking in sensitized 304 stainless steel in high-purity deionized water containing 1.5 ppm dissolved oxygen at 95 deg. C. Crack growth was studied under cyclic loading and under slow strain-rate monotonic rising load. The cylic loading variables were loading rate (loading time), load ratio (R) and K_{max}. Cyclic crack growth rate data were also generated in dry argon and laboratory air for comparison purposes.

Ford and Silverman developed a correlation between cyclic crack growth rate (da/dN) and loading time for various ΔK and R values. The general trend was for crack growth rates to increase with increasing loading time (i.e., the portion of the loading cycle under which the load rises); although at high ΔK values and/or low R values, da/dN was relatively insensitive to loading time. The most pronounced sensitivity to loading time occurred under ripple-loading conditions, i.e., low ΔK and high R values. At long loading times ($\geq 10^3$ seconds), there was a tendency for all data to converge irrespective of ΔK or R values.

Ford and Silverman developed an operative definition of K_{Iscc}; namely, the stress-intensity value below which the "environmentally-controlled" crack growth rate was negligable, i.e., $\leq 10^{-8}$ cm/second. The environmentally-controlled crack growth rate under cyclic loading is determined by subtracting the inert environment (dry argon) da/dN value from the da/dN value measured in the corrosive environment, i.e., by applying the concept of linear superposition to determine total crack growth rates in corrosive environments [14-16].

Using the approach described above, they developed a plot of K_{Iscc} versus loading time for $R \leq 0.1$ (sic). For loading times $\geq 10^4$ seconds, the "dynamic" K_{Iscc} approached the "static" value. For loading times $\leq 10^{-1}$ seconds, the "dynamic" K_{Iscc} diminished to about half the "static" value. The trend line of Ford and Silverman's results is shown in Figure 1.

Ford and Silverman concluded that (i) SCC and corrosion-fatigue crack growth are quantitatively interrelatable and (ii) the stress-intensity level above which environmentally-controlled cracking occurs (K_{Iscc}) is a function of loading parameters, namely loading time and load ratio.

In a study published in 1984 [7], Fessler and Barlo reported data from precracked cantilever-beam tests on two samples of X-52 C-Mn pipeline steel (minimum yield strength = 75 ksi) in an aqueous solution of sodium carbonate and sodium bicarbonate at 175 deg. F. and -650 mV (SCE). The stress levels used were sufficiently high to render a linear elastic fracture mechanics analysis invalid and the data, expressed in terms of net-section stress, were presented only for the purpose of providing a qualitiative illustration of the effects of small-amplitude cyclic loading on SCC.

The study involved two separate samples of steel. One sample exhibited a large effect of ripple-loading on SCC and the other sample showed only a minor effect. The reason for this difference is unknown. In the one sample which was affected by ripple-loading, the nominal net-section threshold stress for SCC was reduced by as much as 60 percent due to cyclic loading range of only 3 percent of the maximum stress ($R = 0.97$). The degree of threshold stress reduction due to ripple-loading was dependent on cyclic frequency, with the reduction in apparent threshold level becoming greater as the cyclic frequency decreased. The most pronounced effects of ripple-loading were seen at a very low frequency of approximately 8 x 10^{-7} Hz (approximately one cycle per two weeks). The highest cyclic frequency reported was 5 Hz. At 5 Hz, the apparent threshold level approached the static value. Tests were also reported for a cyclic stress range of 10 percent of the maximum stress (R = 0.90). However, the threshold data trend appears to be primarily a function of cyclic frequency and largely independent of stress range, for the two stress ranges studied. In all cases, cracking was reported to be intergranular which is characteristic of SCC in this material. The trend line for Fessler and Barlo's data is shown in Figure 2.

It is of interest to compare the trend line of Fessler and Barlo's data, Figure 2, with that of Ford and Silverman, Figure 1. At first glance the two plots appear similar. However, it is important to note that, in Figure 1, the threshold parameter is plotted as a function of loading time and, in Figure 2, the threshold parameter is plotted as a function of cyclic frequency. Loading time and frequency are inversely related. Thus, Ford and Silverman found the threshold to be depressed under rapid cyclic loading, and Fessler and Barlo found the threshold to be similarly affected under slow cyclic loading. Another difference between these two plots is the R-values involved. Figure 1 refers to data for $R \leqslant 0.1$ and Figure 2 is for $R \geqslant 0.9$. Thus, the role of cyclic loading in affecting apparent SCC thresholds is not necessarily the same under all loading conditions.

Because of the high stresses used by Fessler and Barlo, specimens were cycled under full load for about three days prior to introducing the environment in order to exhaust any mechanical creep that might occur. They concluded that the sensitivity of a material to SCC under ripple-loading conditions would depend upon the creep resistance of the material. Clearly, the high stress levels used by Fessler and Barlo clouds the quantitative interpretation of their findings.

In a related study [21], Evans and Parkins conducted room-temperature creep tests on an annealed C-Mn steel using smooth cylindrical specimens.

Their test procedure was to load the specimens above the yield point and observe the creep strain. When the strain rate produced by the initial loading had fallen below a predetermined value, the specimen was completely unloaded for 60 seconds and the reloaded. In the majority of tests, the cycle period was 10 minutes.

It was observed that load cycling produced additional creep which did not occur under static loading. The amount of creep observed was sensitive to the applied stress. It was postulated that creep induced by cyclic loading is the result of the recovery of properties that occurs during unloading and that this recovery is rapid, occurring within 60 seconds of unloading.

Evans and Parkins concluded (i) that cyclic loading produces a marked increase in the creep rate of a C-Mn steel at room temperature, (ii) that the magnitude of the effect increases rapidly with applied stress, and (iii) that cyclic-induced creep could be a significant factor in SCC.

In a subsequent paper [22], Parkins and Suzuki described SCC studies conducted on smooth specimens of an Al-Ni Bronze in natural seawater at various potentials near the free corrosion potential. Two types of tests were conducted, monotonic slow strain-rate and load-controlled cyclic. The parameter used for assessing cracking susceptibility was the average crack velocity. The primary objective of the work was to determine the loading conditions under which environment-sensitive cracking could be induced in the alloy in seawater at various potentials near the free corrosion potential. Most of the tests were conducted at -150mV (SCE).

The underlying supposition of this investigation was that strain rate is the fundamental loading parameter which controls environmental cracking. The implication being that environmental cracking is dependent upon plastic deformation producing fresh metal surfaces at a faster rate than the oxide formation which produces a protective film.

It was found that the threshold stress for SCC was a function of strain rate, decreasing with increasing strain rate until a minimum value of approximately 60 percent of the yield stress was reached. At lower strain rates, the threshold stress approached the ultimate tensile strength of the material. Under cyclic loading using a triangular waveform at a variety of frequencies ranging from 1.7×10^{-7} to 10 Hz, the threshold stress for SCC was approximately 60 percent of the yield stress, i.e., the minimum value reached in the slow strain-rate monotonic tests.

Parkins and Suzuki concluded that the threshold stresses for SCC are the same for monotonic and cyclic loading over a similar range of strain rates, which suggests that the role of strain rate is the same irrespective of the mode of loading.

Mendoza and Sykes studied the effect of cyclic stresses on the initiation and early stages of crack growth in plain specimens of X60 line pipe steel [6]. The stress cycle consisted of a saw-tooth waveform at frequencies of 10^{-3} to 10^{-6} Hz. The potential was controlled at -600 mV versus Ag/AgCl in M/2 Na_2CO_3 + M $NaHCO_3$ at 355 deg. K. All data reported were obtained from electropolished specimens, as SCC cracks did not initiate in mechanically polished specimens. Test results are described in terms of three parameters: maximum stress, load ratio (R = 0.933, 0.90 and 0.75) and cyclic frequency.

A threshold stress was observed, approximately 65 percent of the yield strength, below which SCC cracks did not initiate. Above this threshold, crack initiation was observed and the number of cracks initiated increased with increasing stress. Crack density increased with increasing R value and with decreasing frequency. Crack growth rates (da/dt) also increased with decreasing cyclic frequency.

Mendoza and Sykes concluded that cyclic loading promotes SCC by causing creep at the crack tip. They postulated that ripple-loading could induce Stage I SCC crack growth and cause cracking below the "static" K_{Iscc} level, but that ripple-loading should not affect Stage II (K-independent) SCC crack growth.

In a 1984 paper [23], Liaw et al described a ripple-loading study on a martenstitic quenched-and-tempered 422 stainless steel with a yield strength of 120 ksi. The corrosive environment was boiling NaCl solution at a temperature of 110 deg. C containing 20 ppb dissolved oxygen.

Fatigue testing was conducted using controlled K_{max} values with variable ΔK and R values. Cyclic loading was conducted using a sinusiodal waveform at frequencies of 160 and 16 Hz.

Under loading conditions involving ΔK values near 1.8 ksi$\sqrt{in.}$ (2 MPa$\sqrt{m}$) and R values near 0.9, a K_{max}-independent transition from cycle-dependent to time-dependent cracking was observed. This transition in the nature of the crack growth process was correlated with a transition from transgranular to a mixture of intergranular and transgranular fracture. Liaw et al suggest that below this transition point, cycle-dependent corrosion-fatigue crack growth is the dominant mode of crack extension; above the transition, time-dependent Stage-II SCC becomes dominant. Changing the frequency from 160 to 16 Hz at ΔK values above the transition confirmed the time-dependent nature of the cracking process in the hypertransitional region.

Liaw et al speculate that the effect of ripple-loading in this study may be to reduce the incubation time for SCC to occur by disturbing the formation of oxides at the crack tip, thus producing fresh metal surfaces and enhancing the opportunity for hydrogen embrittlement to occur.

Endo et al conducted sustained-load and cyclic-load tests on two high-strength aluminum alloys sensitive to SCC using WOL-type fracture mechanics specimens [24]. The two alloys were a commercial Al-Zn-Mg material, ZK141 (yield strength = 46 ksi), and an Al-Zn-Mg-Cu alloy, 7075 (yield strength = 60 ksi). The environment was circulating 3.5 percent NaCl solution in deionized water at a constant temperature of 24 deg. C.

SCC tests were performed under static load with and without small vibratory stresses superimposed. The vibratory stresses had a sinusoidal waveform and a frequency of 30 Hz. SCC tests under dynamic loading (ripple-loading) were conducted with R values varying between 0.85 and 0.98. The SCC threshold stress-intensity factor under dynamic loading was termed "K_{Dscc}".

The SCC threshold in the ZK141 alloy was more strongly affected by dynamic loading than was the threshold in the 7075 alloy. For the ZK141 alloy, the K_{Dscc}/K_{Iscc} ratio varied from 1.0 at R = 0.98 to 0.43 at R = 0.85. This reduction in the apparent SCC threshold as a function of ripple-loading was considered by Endo et al to be caused by damage of passive films. Mechanistically, this type of environment-sensitive fracture is considered by Endo et al to differ from that of environmentally-accelerated fatigue crack growth at lower R and higher ΔK values, where cyclic plasticity at the crack tip not only damages passive films but also causes crack growth to occur by mechanical mechanisms such as slip.

Endo et al also conducted an experimental investigation of corrosion-assisted crack growth under static and cyclic loading in a quenched-and-tempered SNCM 439 steel (similar to AISI 4340) with a yield strength of approximately 250 ksi (1725 MPa) using precracked specimens [25]. A positive sawtooth waveform was used at R values of 0.1, 0.3, 0.5, and 0.8 and cyclic frequencies of 0.1 and 5.0 Hz. The corrosive environment was 1 N - H_3BO_3 + 1/30 mol/L - KCl in a circulating mode at a constant temperature of 25 deg. C. The reference environment was dry air containing < 2 ppm water vapor. A static K_{Iscc} value was also obtained.

Data for both cyclic frequencies were plotted on two formats, da/dN-versus-ΔK and da/dt-versus-K_{max}. When the da/dt-versus-K_{max} data for 0.1 and 5.0 Hz are compared with the static K_{Iscc} value, both sets of data clearly indicate that, under cyclic loading, crack growth occurs for $K_{max} < K_{Iscc}$. The degree of crack growth under these conditions was found to be a function of R, with da/dt values varying inversely with R.

Brazill et al conducted an experimental study of environmental cracking in 2-1/4Cr-1Mo steel under both cyclic and sustained loading [26]. Fracture mechanics tests using precracked specimens were conducted on 1-in. (25.4-mm) thick plate material with a yield strength of approximately 110 ksi (750 MPa). Fatigue crack growth and SCC experiments were carried out in hydrogen, water vapor and hydrogen sulfide gaseous environments over a range of temperatures and pressures. The fatigue tests were conducted under sinusoidal loading at 5 Hz and R = 0.1.

Brazill et al found that environmental cracking under sustained load (SCC) could not be obtained in this material under the specific enivronmental conditions examined. However, considerable enhancement of fatigue crack growth rates did occur in hydrogen and in hydrogen sulfide. This indicated that the processes of fatigue provided fresh crack surfaces to react with the environment. From a mechanistic standpoint, these gas/metal reactions are essential to the subsequent embrittlement and cracking processes. From an engineering standpoint, the apparent immunity of the material to SCC does not necessarily imply the same immunity to corrosion-enhanced fatigue crack growth.

The authors conducted a recent study on the influence of small-amplitude cyclic loading on SCC of high-strength steels in salt water [8]. In this investigation, SCC under ripple-loading conditions was studied in 5Ni-Cr-Mo-V (yield strength = 130 ksi) and 4340 (yield strength = 180 ksi) steels in room-temperature 3.5 percent NaCl aqueous solution. Time-to-failure data was developed as a function of initial stress-intensity in precracked cantilever-beam fracture mechanics specimens under static loading and under ripple-loading at R values of 0.90 and 0.95. The 5Ni-Cr-Mo-V steel was cathodically polarized to approximately -1.0 V (versus Ag/AgCl) by coupling to a zinc anode and the 4340 steel was tested at the freely corroding potential.

In the 4340 steel, no significant effect of ripple-loading on time-to-failure data was observed. However, in the 5Ni-Cr-Mo-V steel, both time-to-failure and the apparent K_{Iscc} were significantly reduced by ripple-loading. For R = 0.90, the apparent K_{Iscc} threshold value was at least 40 percent below that for the statically-determined case. The trend lines for the authors' data are shown in Figure 3. From the results of this exploratory investigation, the authors concluded that a statically-determined value of the K_{Iscc} parameter can represent a nonconservative upper-bound measure of SCC sensitivity when applied to service conditions involving small-amplitude cyclic loading at high R values.

Recently, Dover and coworkers have developed a new test method for SCC involving the use of a slowly increasing ramp load over several hundred hours of testing [27]. Superimposed on the slow-rising ramp load are small-amplitude cyclic loads, on the order of one to two percent of the mean load. However, Dover's work has not yet reached the point where the effect of the small-amplitude cyclic loading on SCC under slowly rising load can be determined.

DISCUSSION

The experimental studies cited above clearly demonstrate that cyclic loading can act to promote environmental cracking in many instances. However, it is difficult to discern more than a very broad trend from the rather sparse and diverse research conducted on the subject to date. Nevertheless, the trends reported in this review do cast doubt upon the significance of much of the SCC data generated by traditional static test methods.

It is perhaps significant that several of the most noteworthy examples of ripple-loading effects have been observed in low-to-intermediate strength steels (4,5,7,8,9]. This could be construed as being consistent with Ford's modeling of SCC in the ductile alloy/aqueous environment system, which is based upon the slip/dissolution mechanism [28]. According to Ford's concept, for SCC to occur cracks must have a high aspect ratio of depth-to-width and the sides of the cracks must be relatively inert.

The chemically active region is largely confined to the crack tip and crack-tip strain rate is the primary mechanical parameter controlling crack advance. Ripple-loading contributes to SCC through its influence on crack-tip strain rate. Thus, SCC occurs when the protective film within the crack is thermodynamically stable, but, if the film is ruptured as if by ripple-loading, dissolution of the underlying plastically deformed crack-tip metal is thermodynamically possible. It remains to be seen if such a scenario involving localized film rupture at crack tips caused by ripple loading has the same effect on SCC in high-strength alloys where hydrogen embrittlement is the operative mechanism of crack advance. Hauser and Crooker's limited data on 4340 steel suggest that such may not be the case [8].

It is also unclear where the semantic separation between SCC and corrosion fatigue should occur. Scientifically, this is possible where SCC and corrosion fatigue occur by distinctly different mechanisms, which can be separately identified after the fact by electron microscopy [4,7,23]. However, on a more empirical basis, it is very difficult to separate the two phenomena. This is especially so in those instances where mechanisitic evidence of the two phenomena appear identical [5,20,29,30]. Further, the issue is complicated from a experimental viewpoint by the findings of several investigators who observed that the most pronounced effects of cyclic loading on SCC occured under very low frequency loading conditions [5,7,31].

Experimentally, the soundest approach may be to characterize SCC under ripple-loading conditions as being the same phenomena as that described by the corrosion-fatigue crack growth threshold (ΔK_{th}) under high R-ratio conditions.

From a basic engineering viewpoint, the findings of this review suggest that an SCC threshold parameter value obtained by traditional methods under static loading must be viewed as largely qualitiative, and perhaps significantly nonconservative, for appplications where even minor load fluctuations occur. This viewpoint suggests that a further understanding of SCC mechanisms under combined static/cyclic loading at high R-ratios and new methods for measuring SCC susceptibility under ripple loading are needed.

CONCLUSIONS AND RECOMMENDATIONS

The overriding conclusion of this literature review is that ripple-loading can have a very significant deleterious effect on SCC susceptibility and that a fundamental understanding of this phenomenon is lacking. This fact must be placed in the context that SCC threshold parameters, and in particular the fracture mechanics parameter K_{Iscc}, are widely regarded as materials properties and are published as such in handbooks developed specifically for use in designing military structures [32].

The information summarized in this review provides further evidence that the concept of a theshold parameter for SCC carries a significant degree of uncertainty [27,33,34]. It must be recognized that: (i) what appears to the investigator as an SCC threshold may, in fact, be imperceptibly slow crack growth, and (ii) an experimentally determined threshold parameter, such as K_{Iscc}, can be a function of many factors, including minor stress fluctuations.

In conclusion, it is recommended that the role of ripple-loading in SCC be investigated, both at the fundamental and applied research levels, in order to further the understanding of SCC failure mechanisms under actual service conditions involving combined sustained and cyclic stresses.

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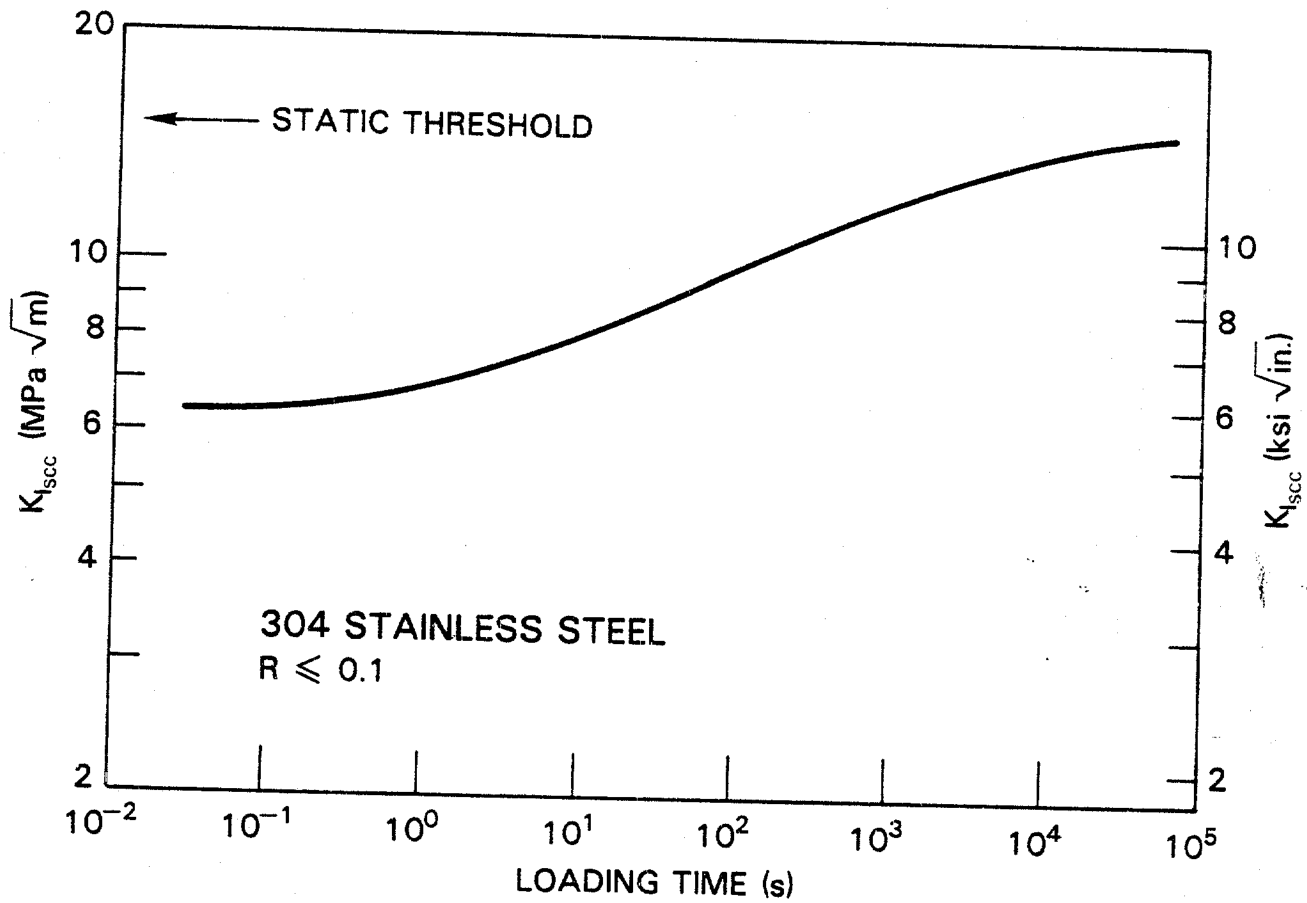

Figure 1 - Trendline of results reported by Ford and Silverman on K_{Iscc} as a function of loading time for sensitized 304 stainless steel in low oxygen deionized water at 95 deg. C [5].

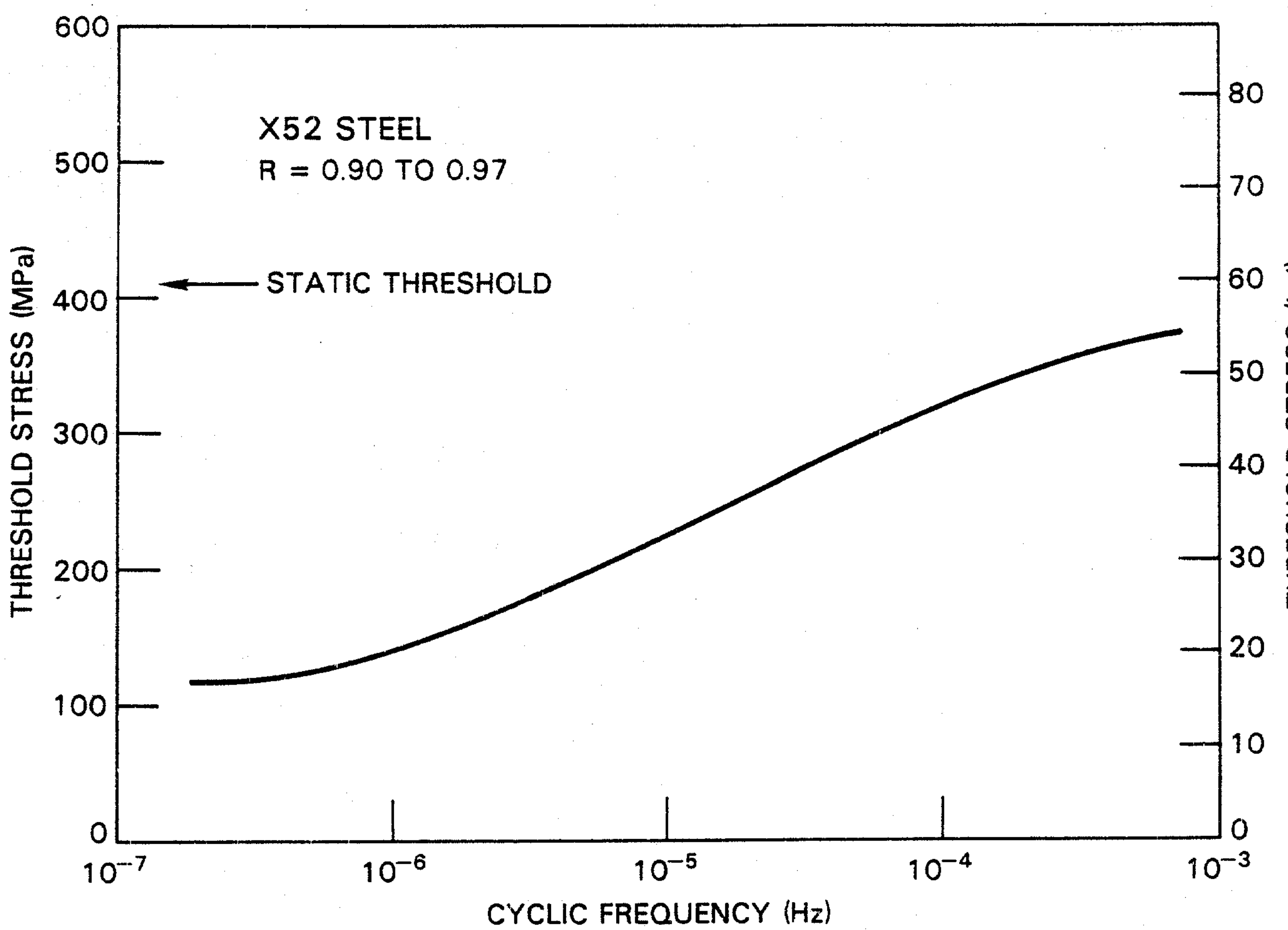

Figure 2 - Trendline of results reported by Fessler and Barlo on the SCC threshold stress as a function of cyclic frequency for X52 steel in an aqueous solution of sodium carbonate and sodium bicarbonate at 175 deg. F (352 deg. K) [7].

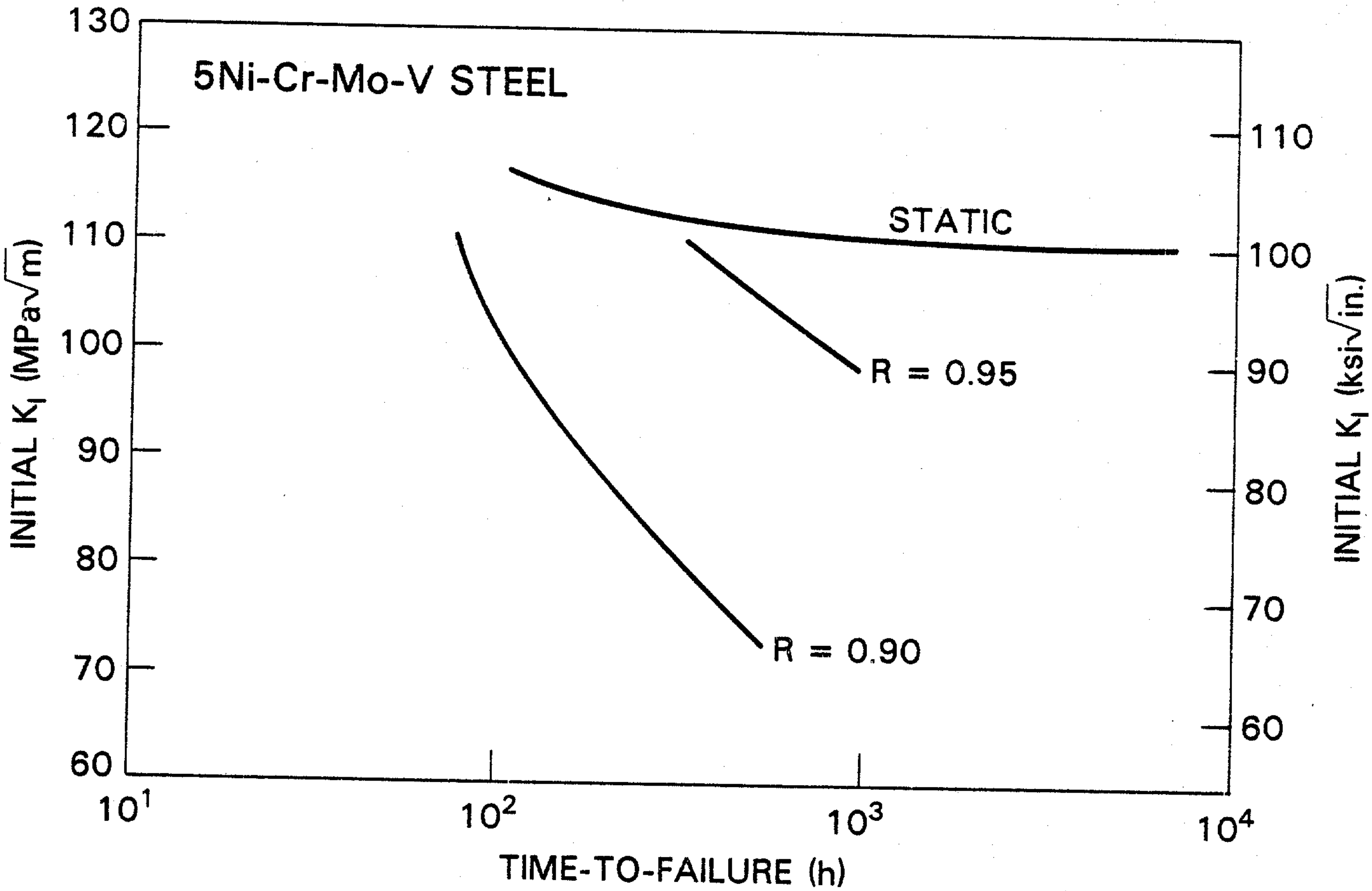

Figure 3 - Trendlines of results reported by Hauser and Crooker showing time-to-failure as a function of initial stress-intensity for 5Ni-Cr-Mo-V steel in salt water at room temperature [8].